Demonstration of a Bias Tunable Quantum Dots in a Well (DWELL) Focal Plane Array (FPA)

Quantum Structure Infrared Photo-detector (QSIP)
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Outline

1. **<u>Motivation</u>**
2. General Overview of DWELL FPA
3. Development of the First and the Second Generation DWELL FPAs
4. Performance Evaluation of DWELL FPA
5. Development and Performance of Non-Uniformity Correction (NUC)
6. Conclusions

Emergence of DWELL Mid-Infrared (IR) Photo-detector

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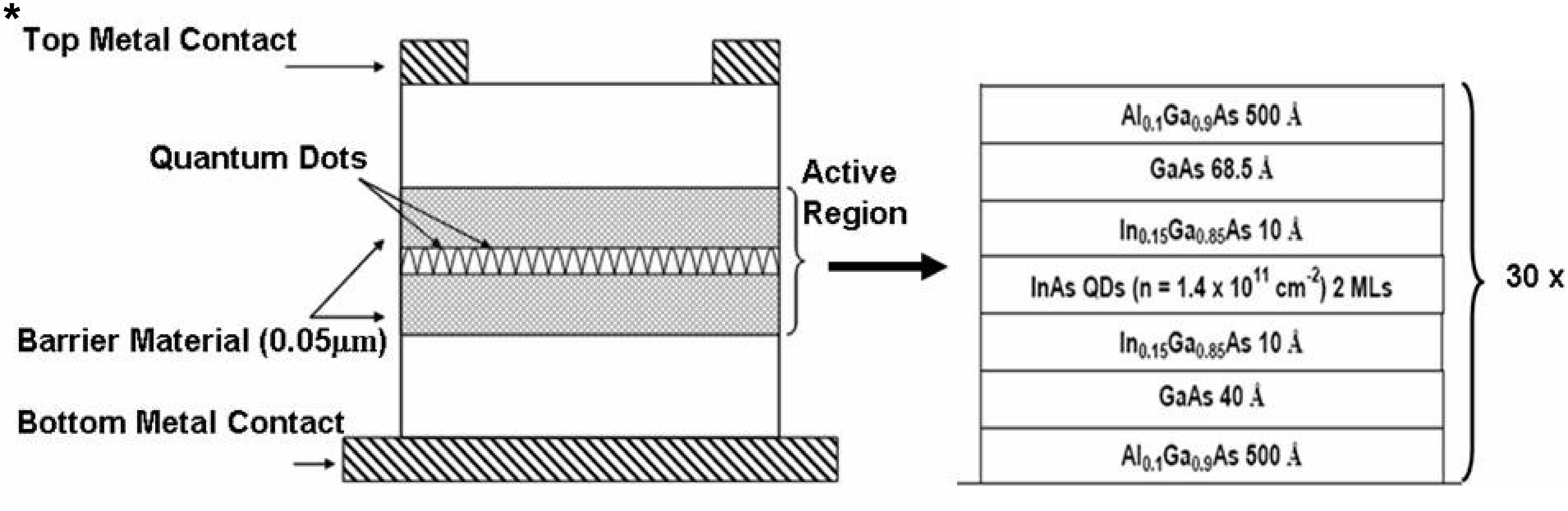
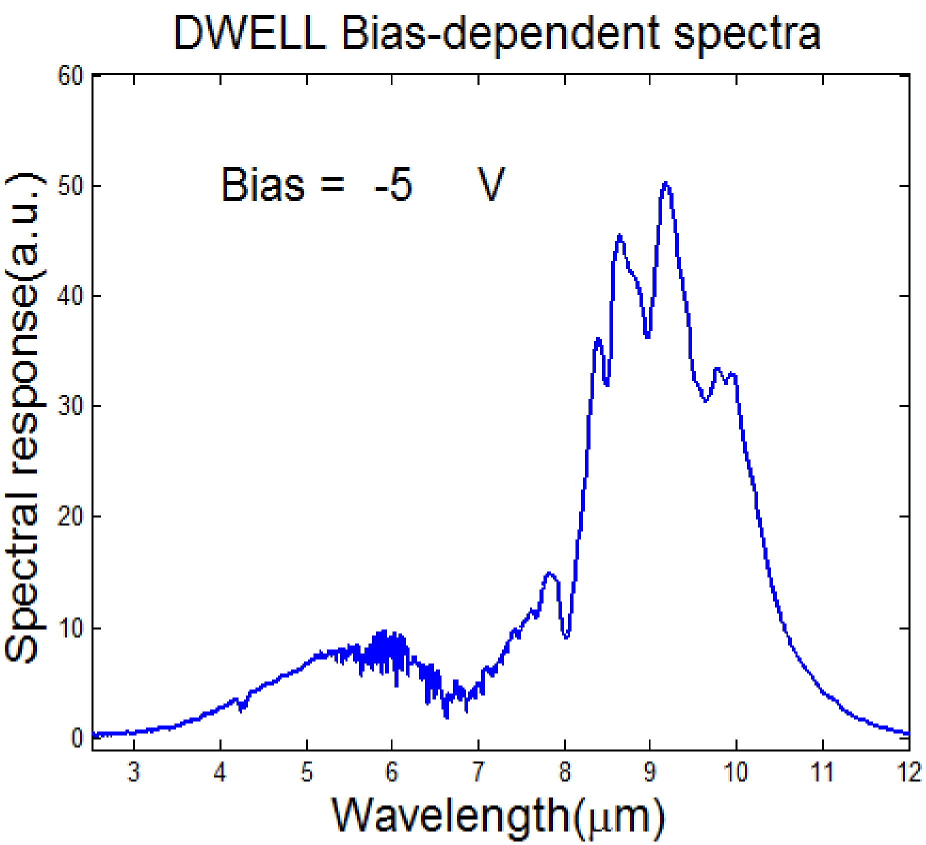
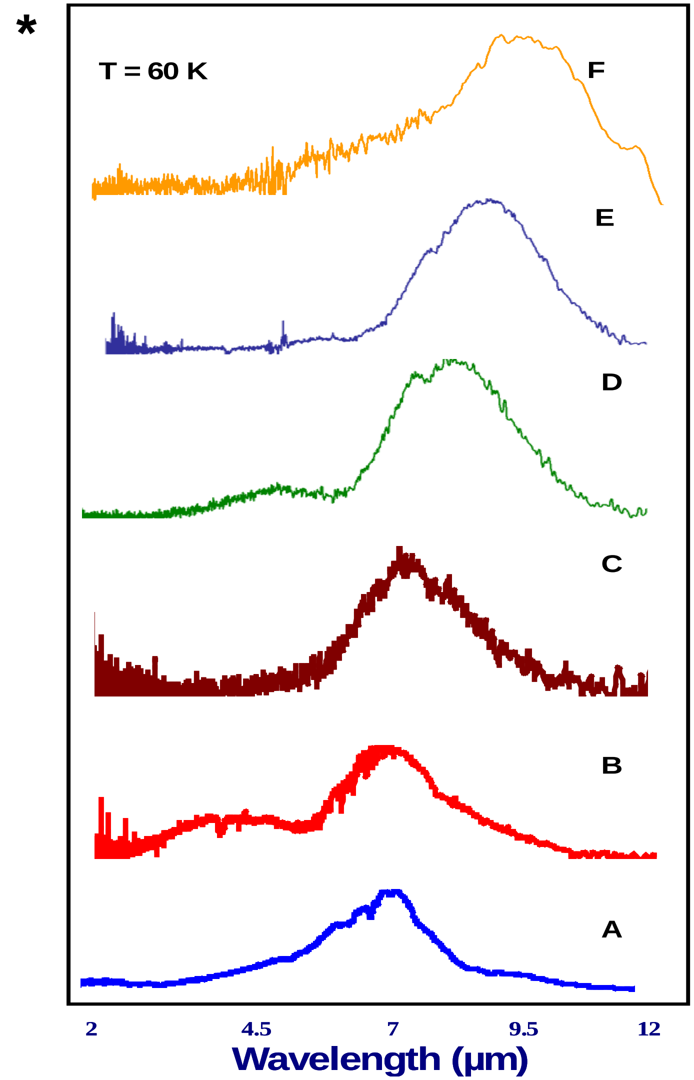


- DWELL is a hybrid of Quantum Well (QW) and Quantum Dot (QD).
- InAs QDs are embedded in InGaAs-GaAs multiple QWs.
- **DWELL structure is capable of reducing thermionic emission → lower dark current → higher device operating temperature by improving photon absorption.**

*****W-Y. Jang, B. Paskaleva, M. M. Hayat, and S. Krishna, "Spectrally adaptive nanoscale quantum dot sensors," *Wiley Handbook of Science and Technology for Homeland Security,* in press, 2008.

Bias Tunability of DWELL





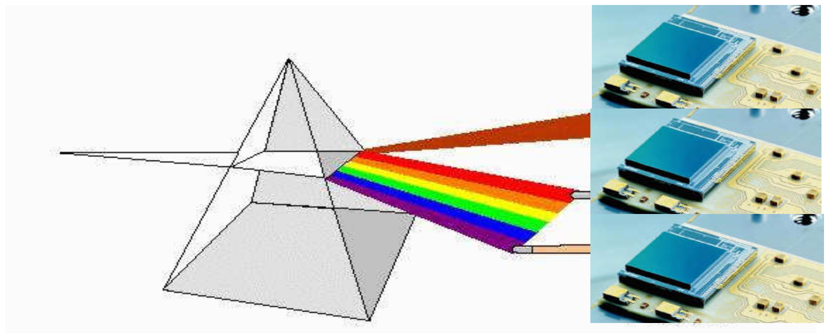
- **Bias tunability leads to the spectral shift ("*red shift*") and the spectral overlap.**

- The operating wavelength and nature of transition can be tailored by varying the width and the material composition of the QW.

***S.** Krishna, "InAs/InGaAs Quantum Dots in a Well Photodetectors," *Journal of Physics D* (*Applied Physics*), vol.38, no.13, p.2142-50, July, 2005.

Multi-color Capability of DWELL

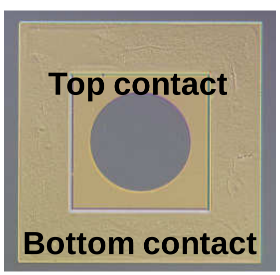
Conventional Multi/Hyper-spectral System

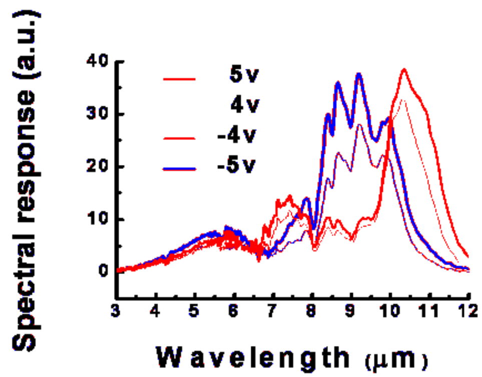


Outputs

- **Multiple detectors are required.**
- Use of a grating to different spectral regions of interest
- A broadband detector with a spinning filter wheel

DWELL based system





Obtain more chromatic information

- **Single DWELL detector can be performed as multiple detectors by bias tunability ("*Spectrally Adaptive*").**

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Structure of Single DWELL Device

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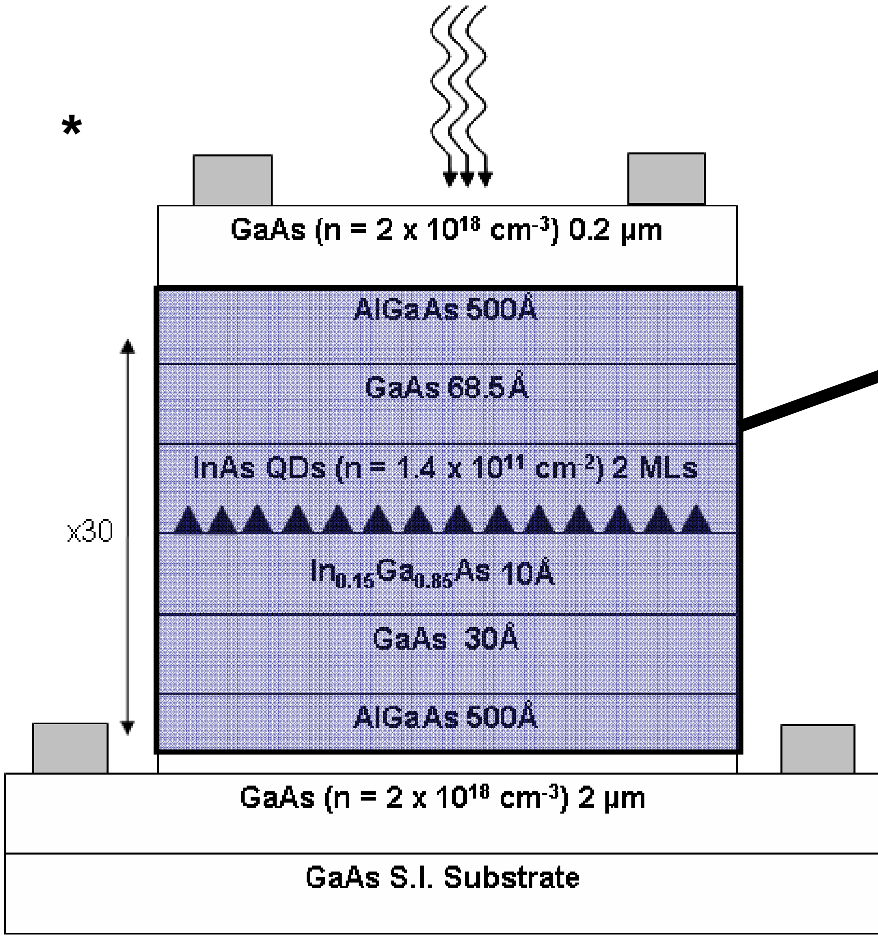
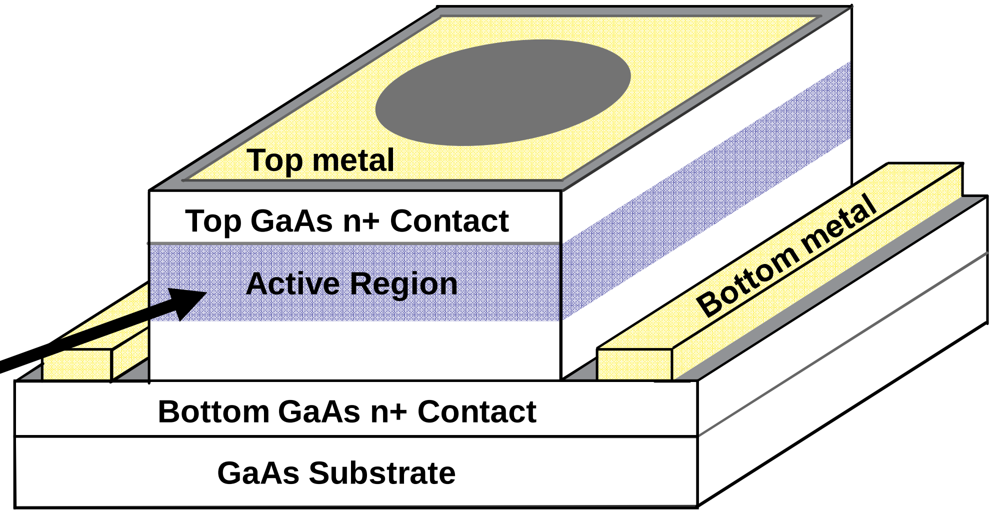
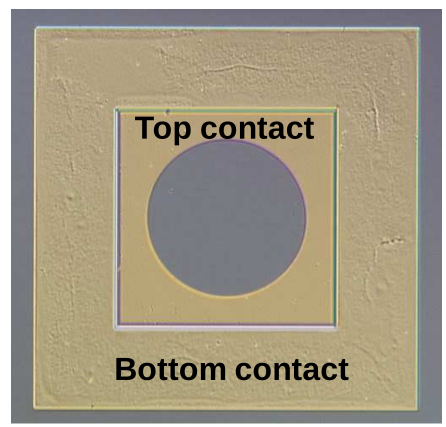




- Active region consists of QDs embedded inside a QW.



- Growth schematic of single pixel detector

- Top view

*W-Y. Jang, M. M. Hayat, J. S. Tyo, R. S. Attaluri, T. E. Vandervelde, Y. D. Sharma, R. Shenoi, A. Stintz, E. R. Cantwell, S. Bender and S. Krishna, "Demonstration of Bias Controlled Algorithmic Tuning of Quantum Dots in a Well (DWELL) Mid-infrared Detectors," *IEEE J. Quantum Electronics,* in press, 2008.

DWELL Research

APPLIED PHYSICS LETTERS VOLUME 81, NUMBER 8 19 AUGUST 2002

High-responsivity, normal-incidence long-wave infrared (λ~7.2 μm) $InAs/In_{0.15}Ga_{0.85}As$ dots-in-a-well detector

S. Raghavan, P. Rotella, A. Stintz, B. Fuchs, and S. Krishna
Center for High Technology Materials, University of New Mexico, Albuqu
C. Morath and D. A. Cardimona
Air Force Research Lab (AFRL/VSSS), 3550 Aberdeen Avenue S. E., Buil
New Mexico 87117
S. W. Kennerly
Army Research Laboratory, Sensors and Electron Devices Directorate, Ad

(Received 6 May 2002; accepted for publication 12 June 2002)

- Various Research Groups are now using DWELL
  - Wilson/David's Group (Sheffield University)
  - IR Nova/Linkoping University (Sweden)
  - Jagadish's Group (Australian National University)
  - J.Deen's Group (McMaster University)
  - Razeghi's Group (Northwestern University)
  - Wang's Group (Taiwan)
  - Gunapala's Group (NASA JPL) etc.

Spectral function of InAs/InGaAs quantum d
using Green's function

M. A. Naser, M. J. Deen,[a] and D. A. Thompson
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West, Hamilton, Ontario L8S 4K1, Canada

(Received 11 July 2006; accepted 22 August 2006; published onl

Energy level structure and electron relaxation tim
quantum dot-in-a-well structures

P. Aivaliotis,[a] S. Menzel, E. A. Zibik, J. W. Cockburn, and L. R. Wilson[b]
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M. Hopkinson
EPSRC National Centre for III-V Technology, The University of Sheffield, Sheffield S1 3JD, United Kingdom

(Received 5 October 2007; accepted 1 November 2007; published online 17 December 2007)

640 × 512 Pixels Long-Wavelength Infrared (LWIR) Quantum-Dot Infrared Photodetector (QDIP) Imaging Focal Plane Array

Sarath D. Gunapala, Sumith V. Bandara, Cory J. Hill, David Z. Ting, John K. Liu, Sir B. Rafol, Edward R. Blazejewski, Jason M. Mumolo, Sam A. Keo, Sanjay Krishna, Y.-C. Chang, and Craig A. Shott

PHYSICAL REVIEW B 78, 115320 (2008)

Gain and recombination dynamics in photodetectors made with quantum n
The quantum dot in a well and the quantum well

B. Movaghar, S. Tsao, S. Abdollahi Pour, T. Yamanaka, and M. Razeghi
Center for Quantum Devices, Electrical Engineering, and Computer Science, Northwestern University, Evanst

(Received 1 May 2008; revised manuscript received 30 July 2008; published 23 September

High quantum efficiency dots-in-a-well quantum dot infrared photodetectors with AlGaAs confinement enhancing layer

H. S. Ling,[1] S. Y. Wang,[2,a] C. P. Lee,[1] and M. C. Lo[1]
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Effects of annealing on the spectral response and dark current of quantum dot infrared photodetectors

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Online at stacks.iop.org/JPhysD/41/215101

Bias and temperature dependence of the escape processes in quantum dots-in-a-well infrared photodetectors

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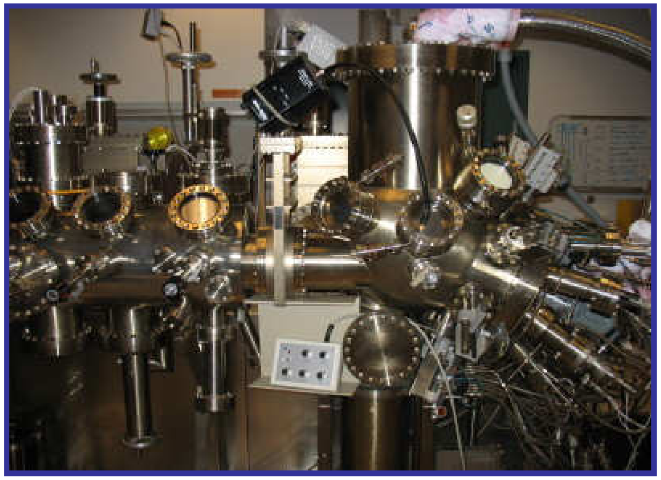
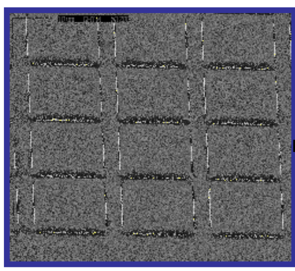
[4]*IRnova, Electrum 236, S-16440 Kista, Sweden*

(Received 11 July 2008; accepted 10 August 2008; published online 8 September 2008)

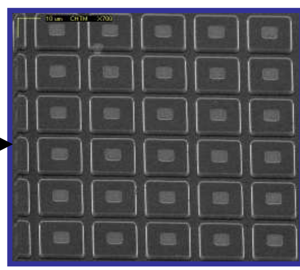
DWELL FPA Fabrication



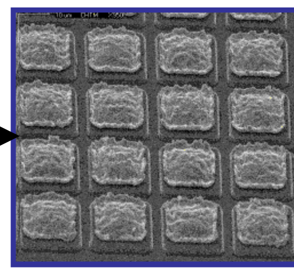
- Material Growth – Molecular Beam Epitaxy (MBE)



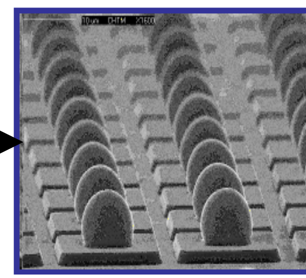
Mesa etched and covered by SiN



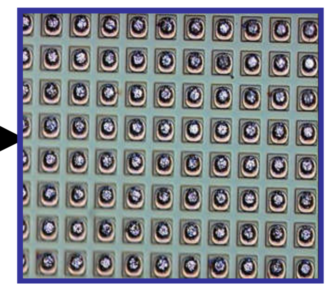
Etched SiN



Fully processed PiN FPA



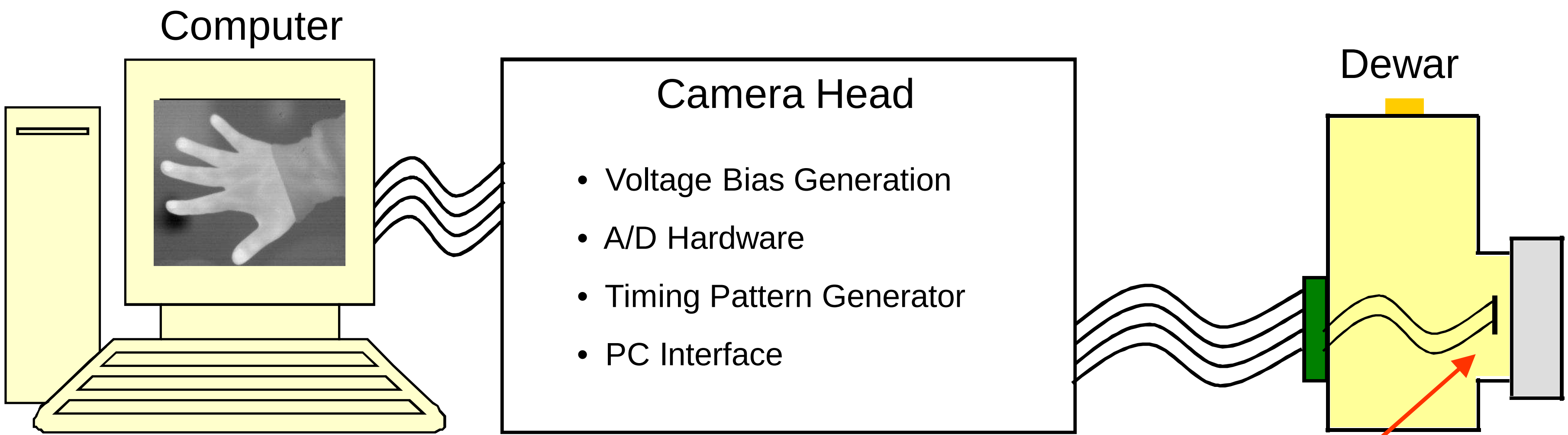
Fully processed PiN FPA after In re- flow



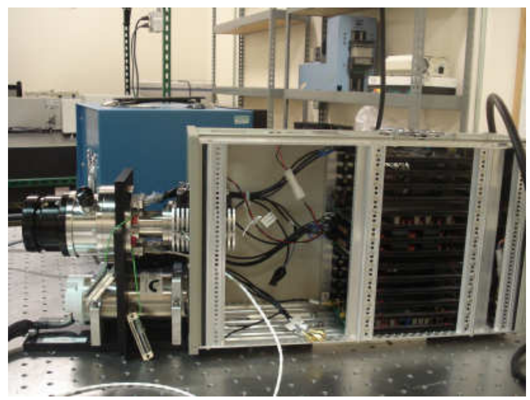
320 x 256 DWELL FPA

- Device processing

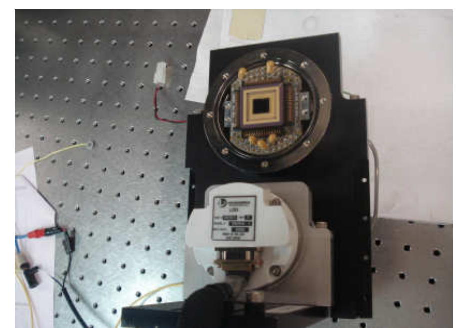
DWELL FPA Test Setup for Device Characterization



- Data Processing & Storage



FPA



- **Commercially available SE-IR CamIRa™ demonstration system:**
  - Janos Technology Ninox 3 ~12 μm lens
  - SE-IR CamIRa software, Closed cycle dewar, Camera Head electronics
  - Extended (plate) Blackbody source

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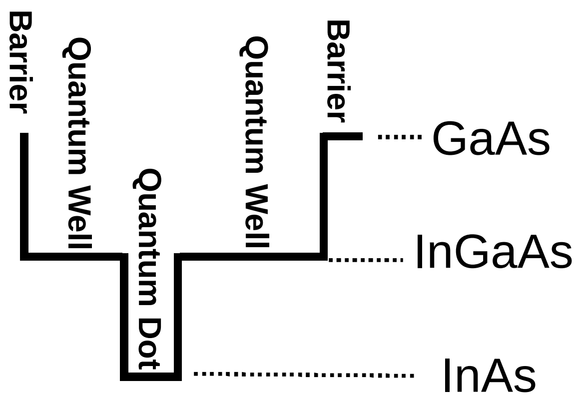
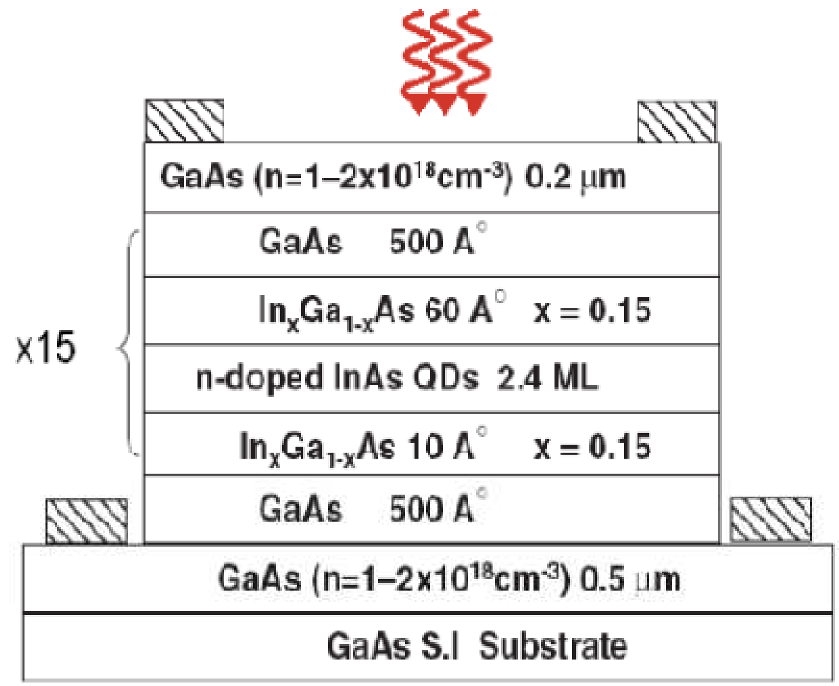
Review of First Generation InAs / InGaAs / GaAs DWELL FPA



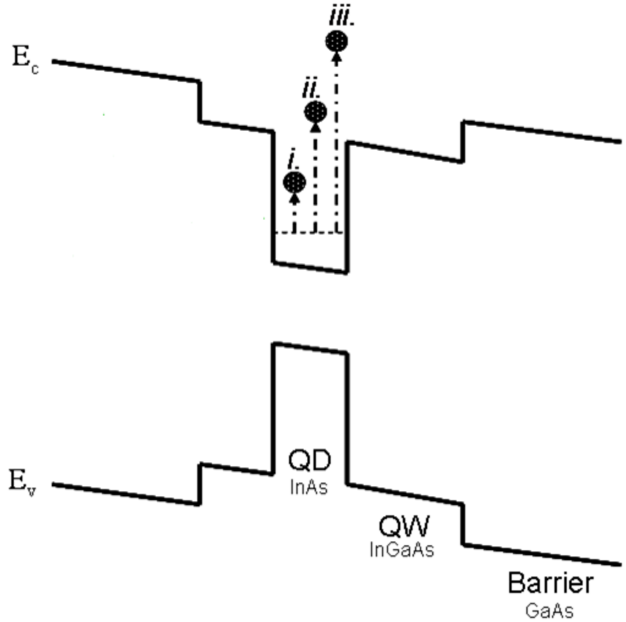
"Standard " DWELL



■ Conduction band-diagram of InAs / InGaAs / GaAs DWELL

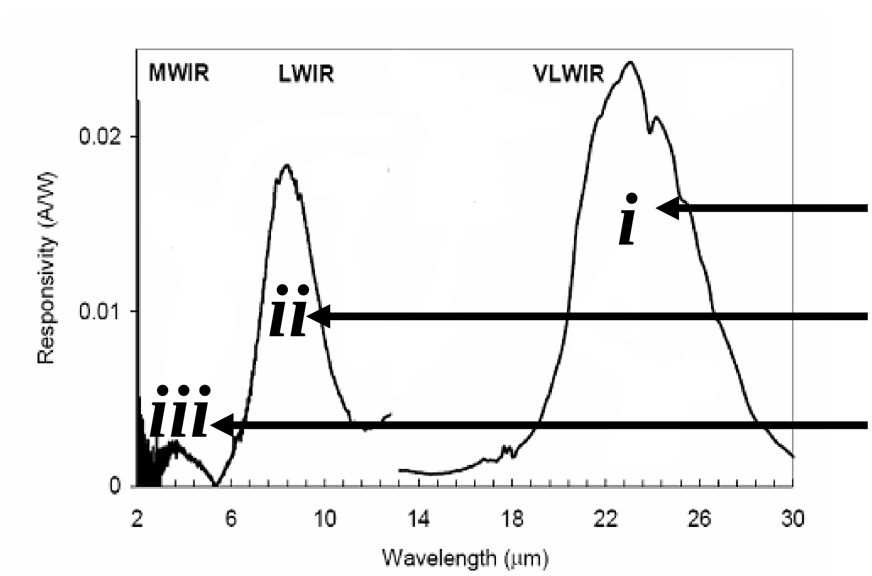
■ Growth schematic of InAs / InGaAs / GaAs DWELL single pixel

☐ Self-assembled QDs due to strain in the system due to lattice mismatch
☐ Limited number of stacks of active region to avoid defects
☐ Quantum efficiency (QE) using this DWELL structure is low.



- Asymmetric conduction and valence band-diagrams describing inter-sublevel transitions:

  i. *Bound-to-bound*
  ii. *Bound-to-quasi-bound*
  iii. *Bound-to-continuum*



- Corresponding spectral responsivity
  - Very long-wave IR (**VLWIR**)
  - Long-wave IR (**LWIR**)
  - Mid-wave IR (**MWIR**)

Development of Second Generation InAs / InGaAs / GaAs / AlGaAs DWELL FPA

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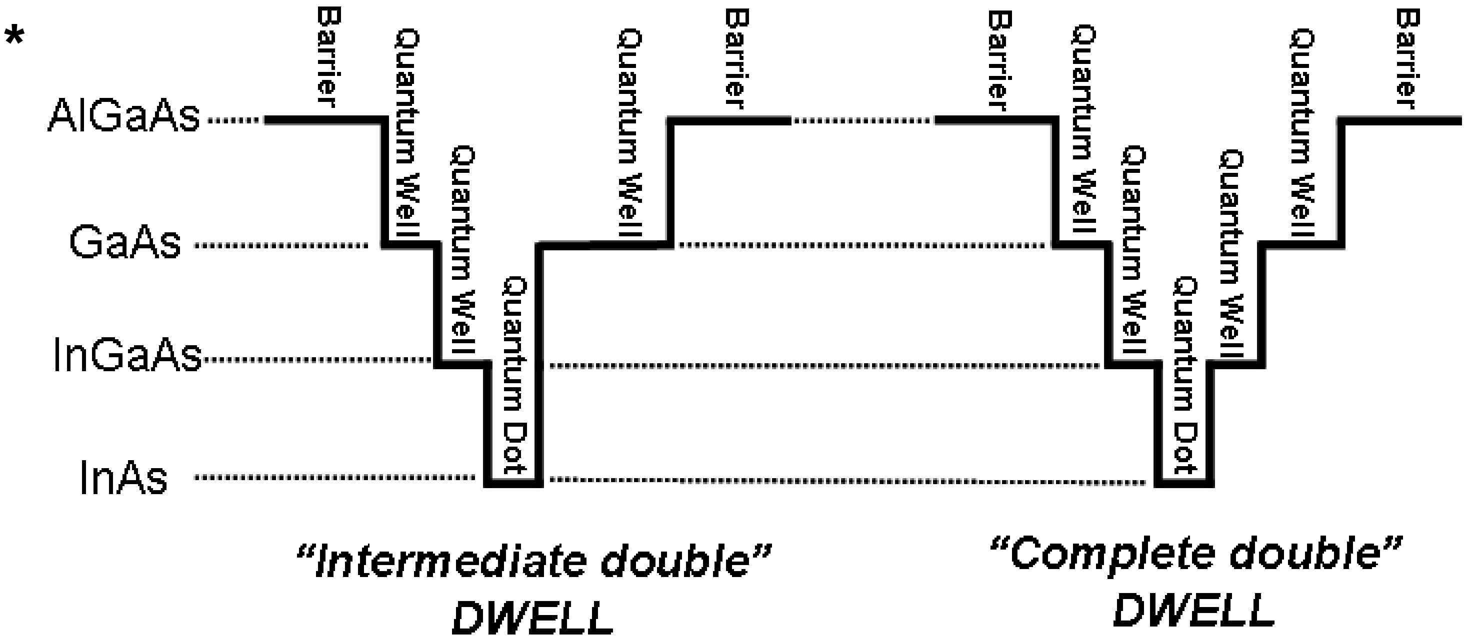

■ Conduction band-diagram of InAs / InGaAs / GaAs **/** AlGaAs double DWELL (**DDWELL**)

☐ **Less strain in active region, leading to maximize the volume of the active region ⟶ A higher number of stacks of active region grown**

⟶ **Improvement of responsivity and QE

(**Reported by Shenoi et al. in JVSTB)

☐ **Higher device operating temperature was observed**.

*****W-Y. Jang, M. M. Hayat, S. C. Bender, Y. D. Sharma, J. Shao and S. Krishna, "Performance enhancement of an algorithmic spectrometer with quantum-dots-in-a-well infrared photodetectors," *IEEE International Symposium on Spectral Sensing Research (ISSSR 08),* June 23-27, 2008.

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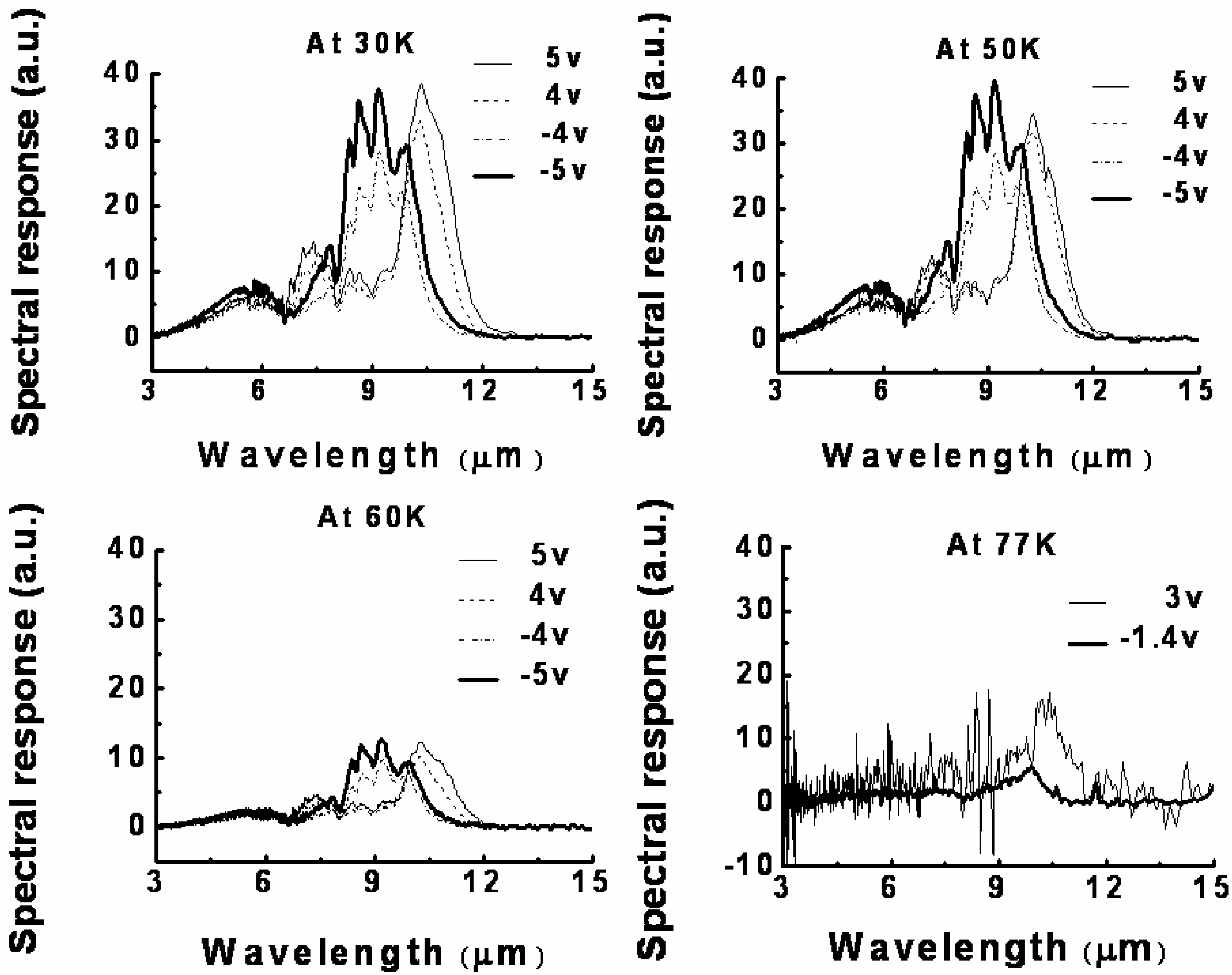

■ Bias-dependent spectral responses of "intermediate" DDWELL for different operating temperatures at (a) 30K, (b) 50K, (c) 60K and (d) 77K.

*W-Y. Jang, M. M. Hayat, J. S. Tyo, R. S. Attaluri, T. E. Vandervelde, Y. D. Sharma, R. Shenoi, A. Stintz, E. R. Cantwell, S. Bender and S. Krishna, "Demonstration of Bias Controlled Algorithmic Tuning of Quantum Dots in a Well (DWELL) Mid-infrared Detectors," *IEEE J. Quantum Electronics,* in press, 2008.

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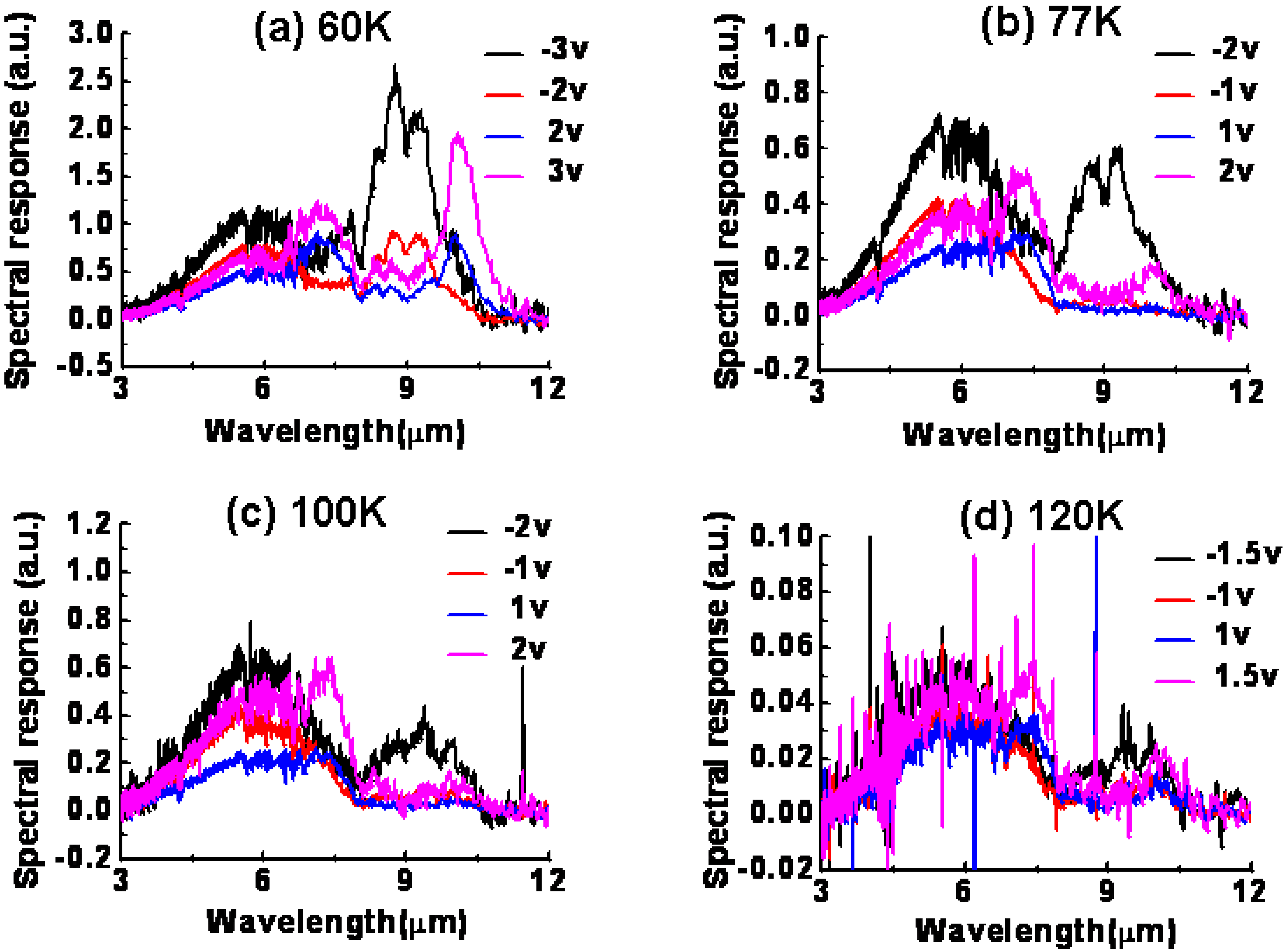

■ Bias-dependent spectral responses of "complete" DDWELL for different operating temperatures at (a) 60K, (b) 77K, (c) 100K and (d) 120K.

*****W-Y. Jang, B. Paskaleva, M. M. Hayat, and S. Krishna, "Spectrally adaptive nanoscale quantum dot sensors," *Wiley Handbook of Science and Technology for Homeland Security,* in press, 2008.

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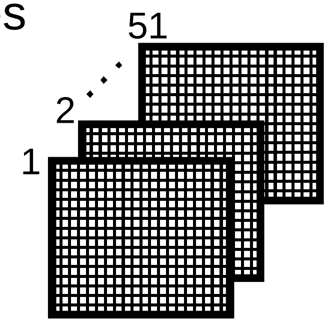
Procedure of Performance Measure

■ For each pixel of the entire 320 x 256 FPA, obtain raw outputs (signal responses in counts) at low, T_1 and high, T_2 , scene temperatures over 51 frames



■ Calculate average responses R_{low} and R_{high} over 51 frames

■ σ at lower scene temperature over 51 frames is the noise value (N) at each pixel

■ Find response-to-noise ratio from $R_s / N = (R_{high} - R_{low}) / N$

■ **NEDT (Noise Equivalent Difference in Temperature)**

□ $\Delta T = T_2 - T_1$

□ R_s = **response between** T_1 **and** T_2

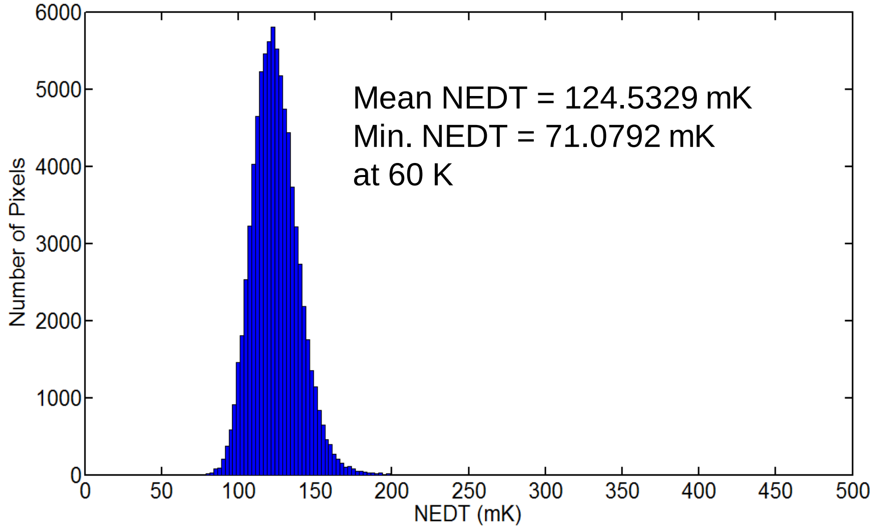
□ **Measure of sensitivity**

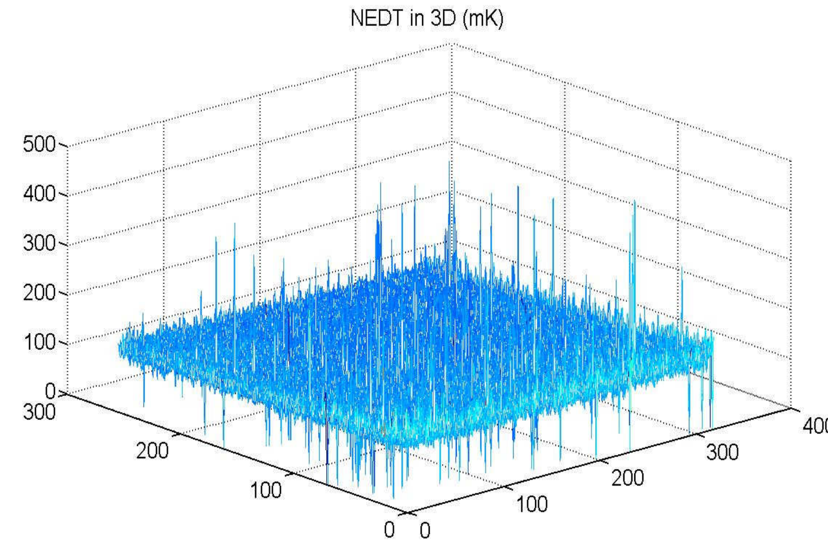
□ **Minimum uniform scene temperature difference a system can detect**

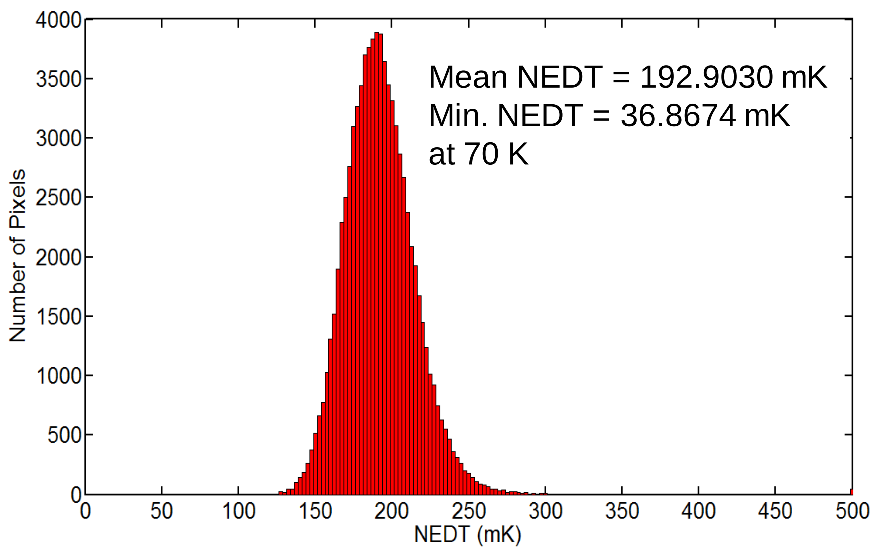
$$^{*}NEDT = \frac{\Delta T}{R_s / N} \;[\mathrm{K}]$$

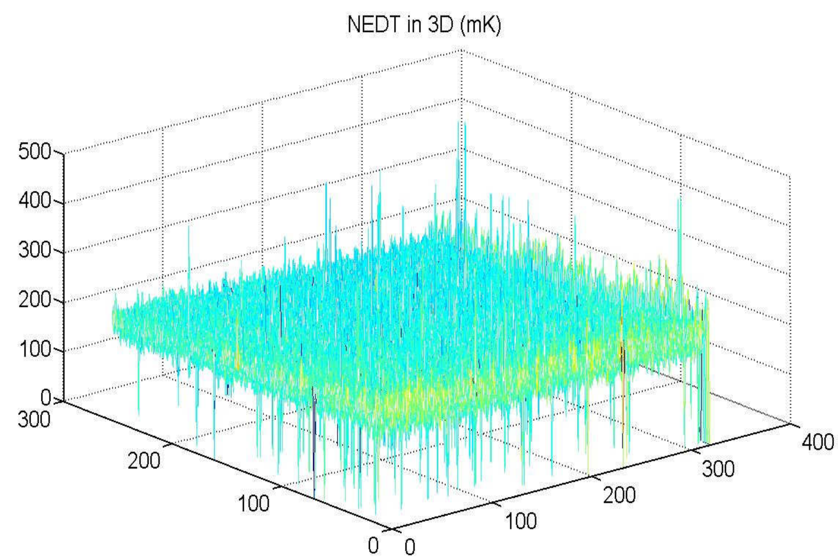
*E. L. Dereniak and G. Boreman, “Infrared Detectors and Systems,” *Wiley,* New York, 1996.

First Generation InAs / InGaAs / GaAs DWELL FPA



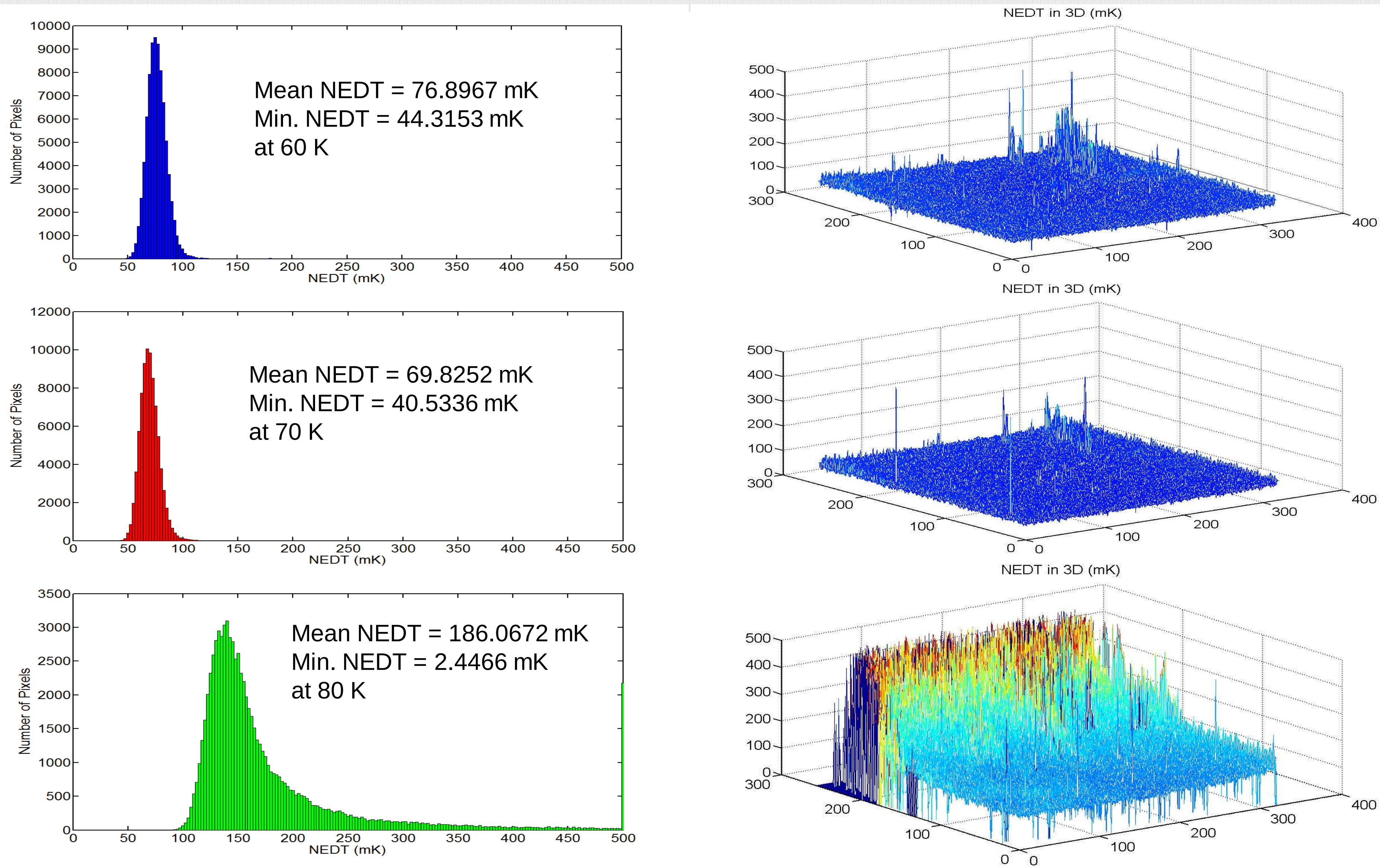






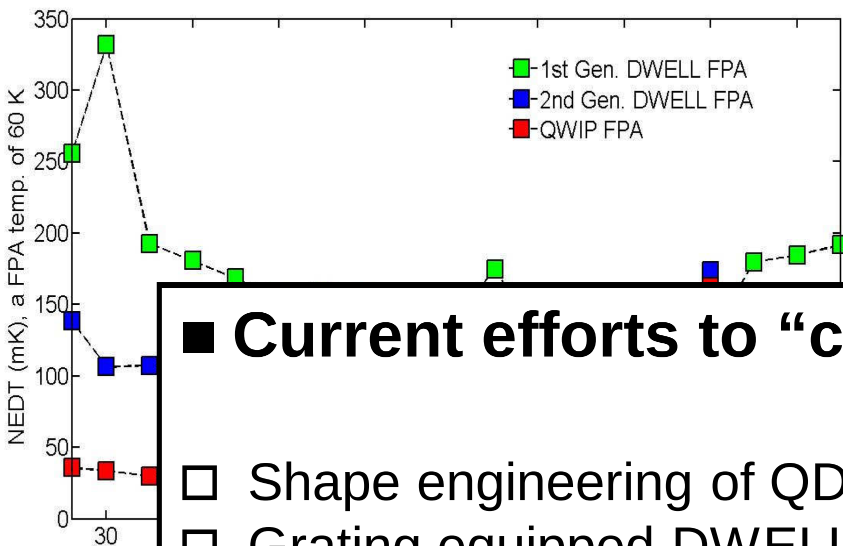
■ Histogram and 3-D plot of NEDT at FPA temperatures and a Bias of 0.82 V

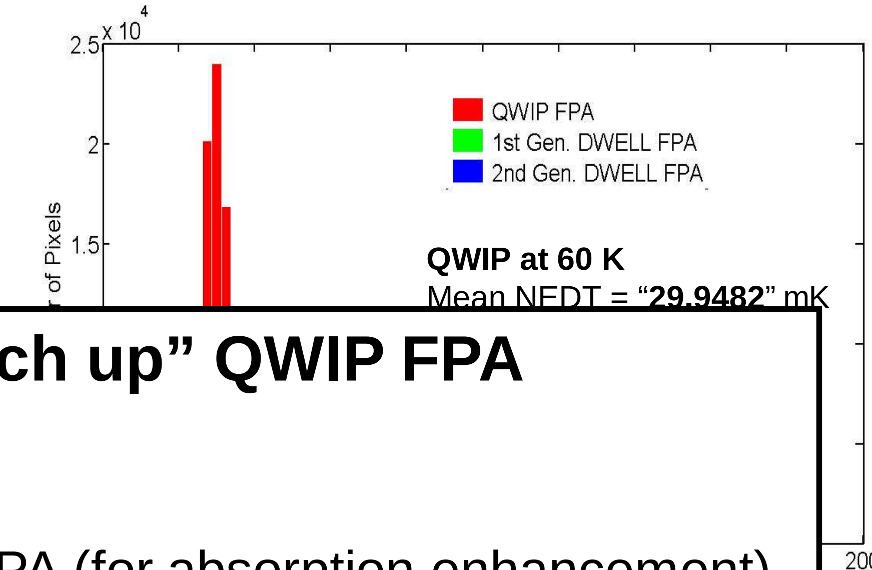
Second Generation InAs / InGaAs / GaAs / AlGaAs DWELL FPA



■ Histogram and 3-D plot of NEDT at FPA temperatures and a Bias of 1.0 V

Comparison of DWELL FPAs with Commerical QWIP FPA

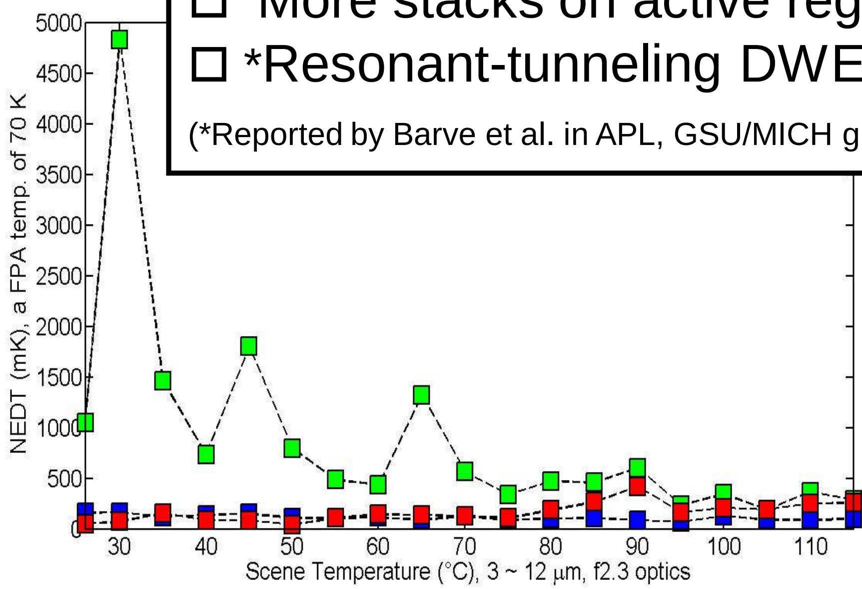


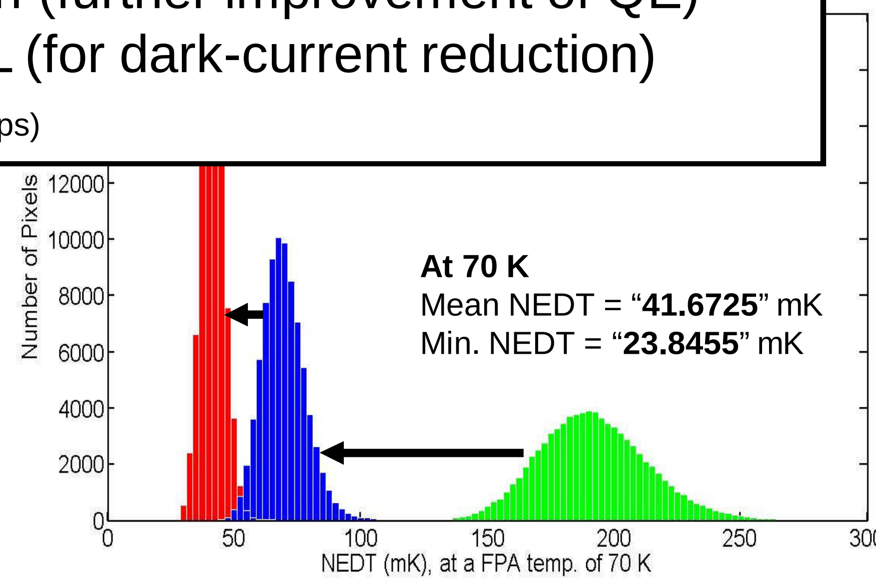


■ Current efforts to "catch up" QWIP FPA

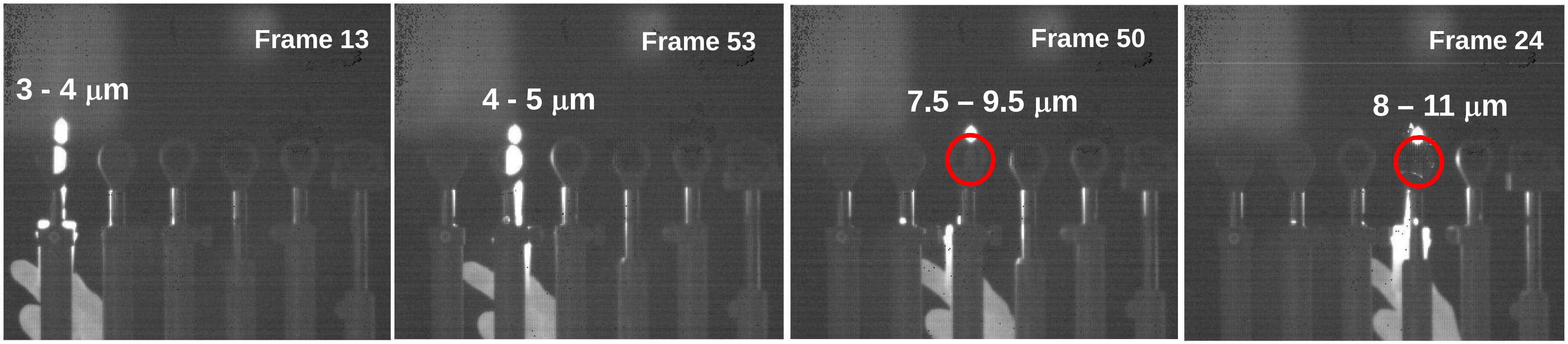
- ☐ Shape engineering of QDs
- ☐ Grating equipped DWELL FPA (for absorption enhancement)
- ☐ More stacks on active region (further improvement of QE)
- ☐ *Resonant-tunneling DWELL (for dark-current reduction)

(*Reported by Barve et al. in APL, GSU/MICH groups)

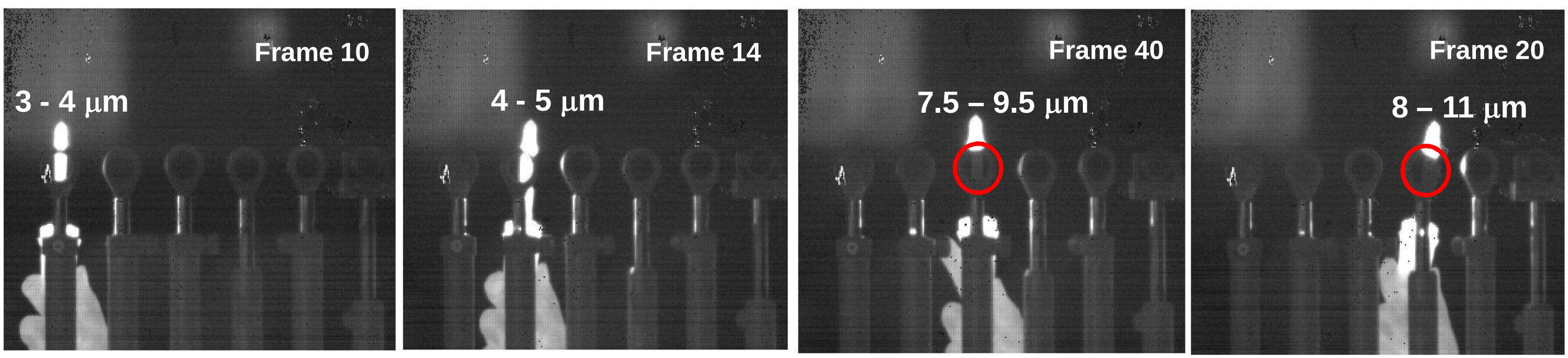




Bias Tunability and Multi-color Capability of Second Generation DWELL (DDWELL) FPA

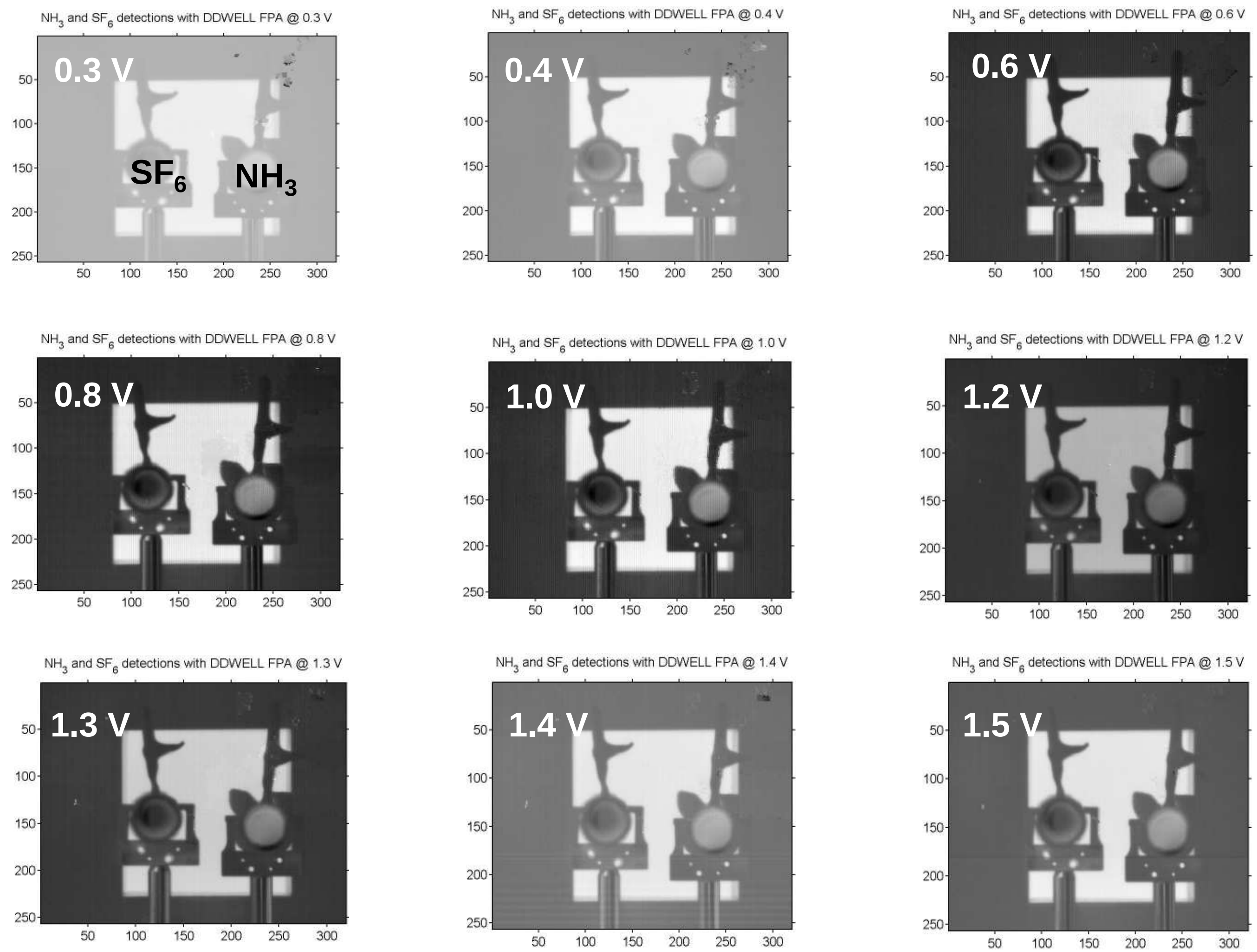


■ NUC scenes are taken at a FPA temperature of 60 K and a bias of 0.5 V using hot soldering iron, six different optical filters with bandwidths (i.e. from left to right, 3 – 4 μm, 4 – 5 μm, 7.5 – 9.5 μm, 8 – 11 μm, 9 – 12 μm and 10 – 13 μm) and 3 – 12 μm lens.



■ NUC scenes are taken at a FPA temperature of 60 K and a bias of 1.3 V

Application of Bias Tunability to SF_6 and NH_3 Gas detections with DDWELL FPA



■ NUC images of SF_6 and NH_3 detected at a FPA temperature of 60 K and various applied biases (V) from 0.3 to 1.5 V.

V_{Bias} (V)	Change in ratio		Description
	SF_6 / BB	NH_3 / BB	
0.3	0.00 (%)	0.00 (%)	NH_3: Outputs obtained by averaging over 630 pixels.
0.4	-2.91 (%)	-1.34 (%)	
0.6	-4.60 (%)	-1.99 (%)	
0.7	-0.67 (%)	0.01 (%)	SF_6: Outputs obtained by averaging over 780 pixels.
0.8	-0.89 (%)	-0.55 (%)	
0.9	1.22 (%)	0.81 (%)	
1.0	2.20 (%)	0.73 (%)	BB: Blackbody considered as a reference. Outputs obtained by averaging over 936 pixels.
1.1	2.46 (%)	0.76 (%)	
1.2	1.54 (%)	0.40 (%)	
1.3	0.26 (%)	0.37 (%)	
1.4	0.52 (%)	0.31 (%)	
1.5	-0.04 (%)	0.02 (%)	

- Overall decrease in ratio

(SF_6 / BB) = **9.07 %** from 0.3 to 0.8 V

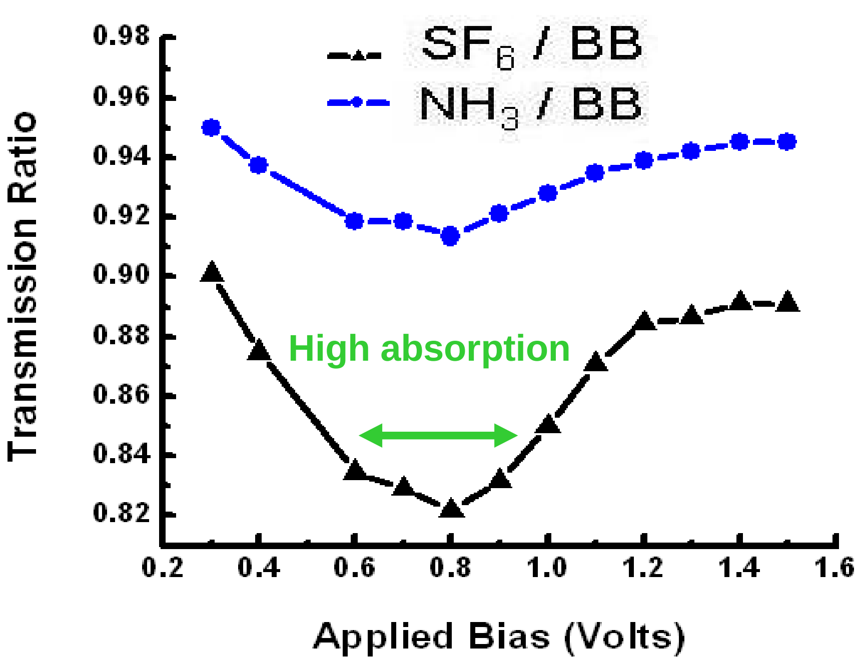
(NH_3 / BB) = **3.87 %**

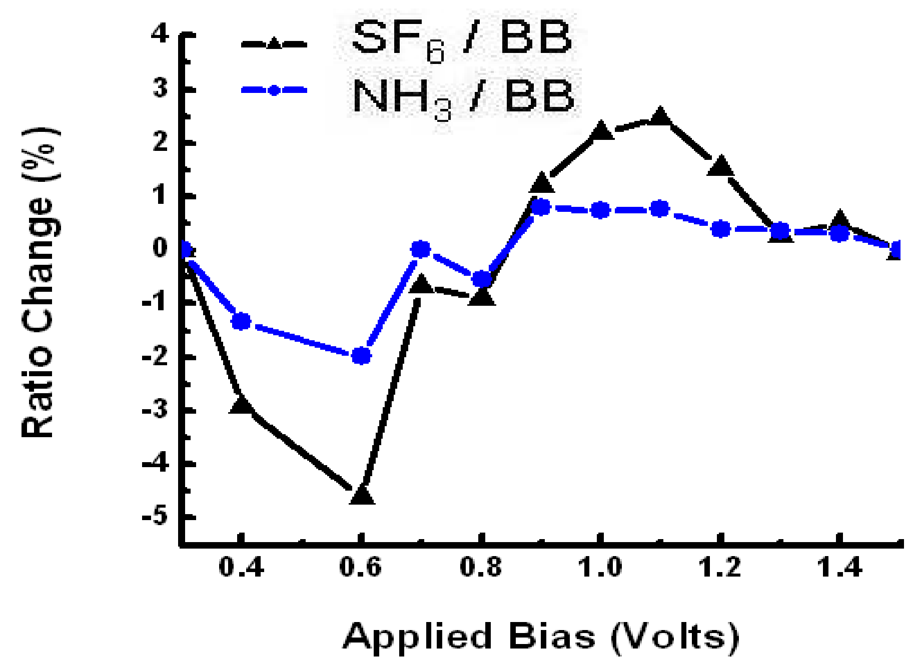
Overall increase in ratio

(SF_6 / BB) = **8.16 %** from 0.9 to 1.5 V

(NH_3 / BB) = **3.4 %**

- **High SF_6 absorptions observed at a bias range from 0.6 to 0.9 V.**





Outline

1. Motivation
2. General Overview of DWELL FPA
3. Development of the First and the Second Generation DWELL FPAs
4. Performance Evaluation of DWELL FPA
5. **<u>Development and Performance of Non-Uniformity Correction (NUC)</u>**
6. Conclusions

Non-Uniformity Correction (NUC): System Model

- In a FPA, the ***gain*** (A) and the ***offset*** (B) parameters determine, at sample-time *k*, the response of the *ij*-th photo-detector:

$$Y^{ij}[k] = A^{ij} T^{ij}[k] + B^{ij} + V^{ij}[k]$$

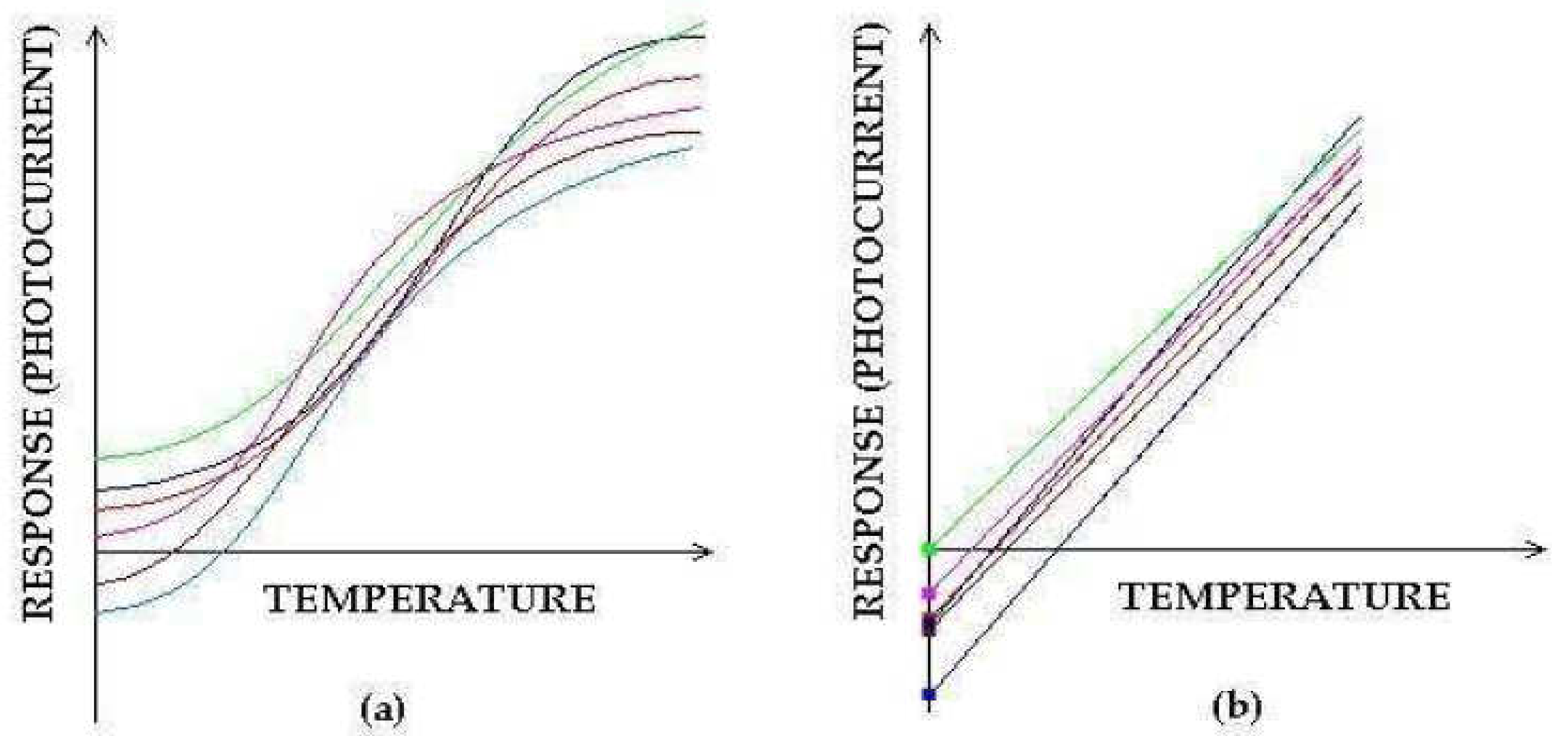
- **Assumptions:**
  - A and B drift slow with sample-time *k*
  - $V^{ij}[k]$ additive zero-mean white noise with know variance s^2

- **NUC** question is: How to obtain the real incident ***radiation data*** (T) from the noisy ***readout data*** (Y)?

- **NUC** goals are:
  - parameter estimation of each photodetector
  - compensation of the corrupted image sequences

Non-Uniformity Correction (NUC): Multiple-Point Calibration

*

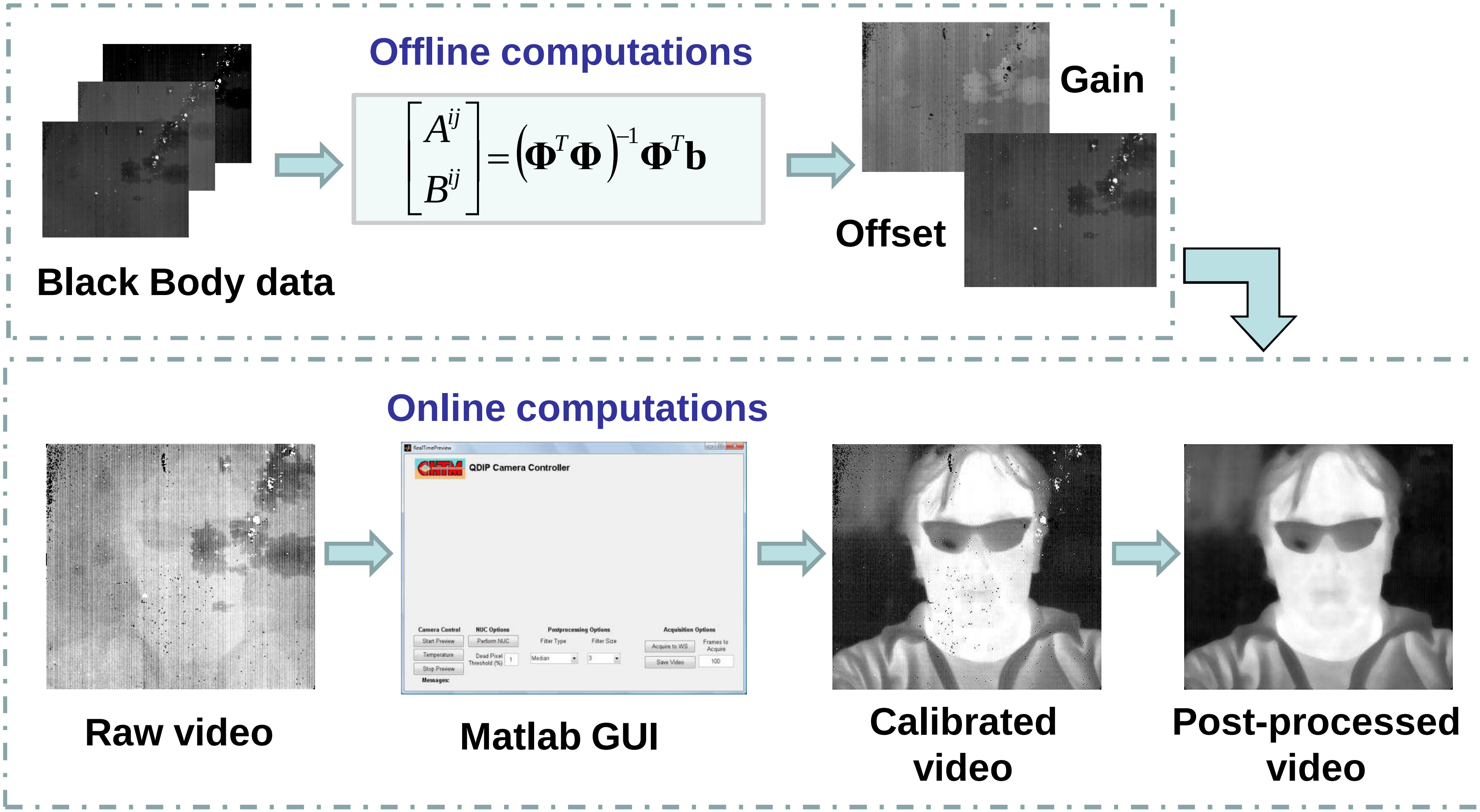


(a) Example of different detector responses to incident temperature

(b) Multiple-point linear approximations of responses

* Unal's Ph.D. dissertation, University of New Mexico, 2006

Calibration and Non-Uniformity Correction



- **Capabilities:**
  - ☐ Real-time NUC and scene-based NUC
  - ☐ Real-time post-processing: Spatial filtering and dead-pixel correction
  - ☐ Temperature measurement, raw and corrected video acquisition

Real-time Multiple-point NUC Results

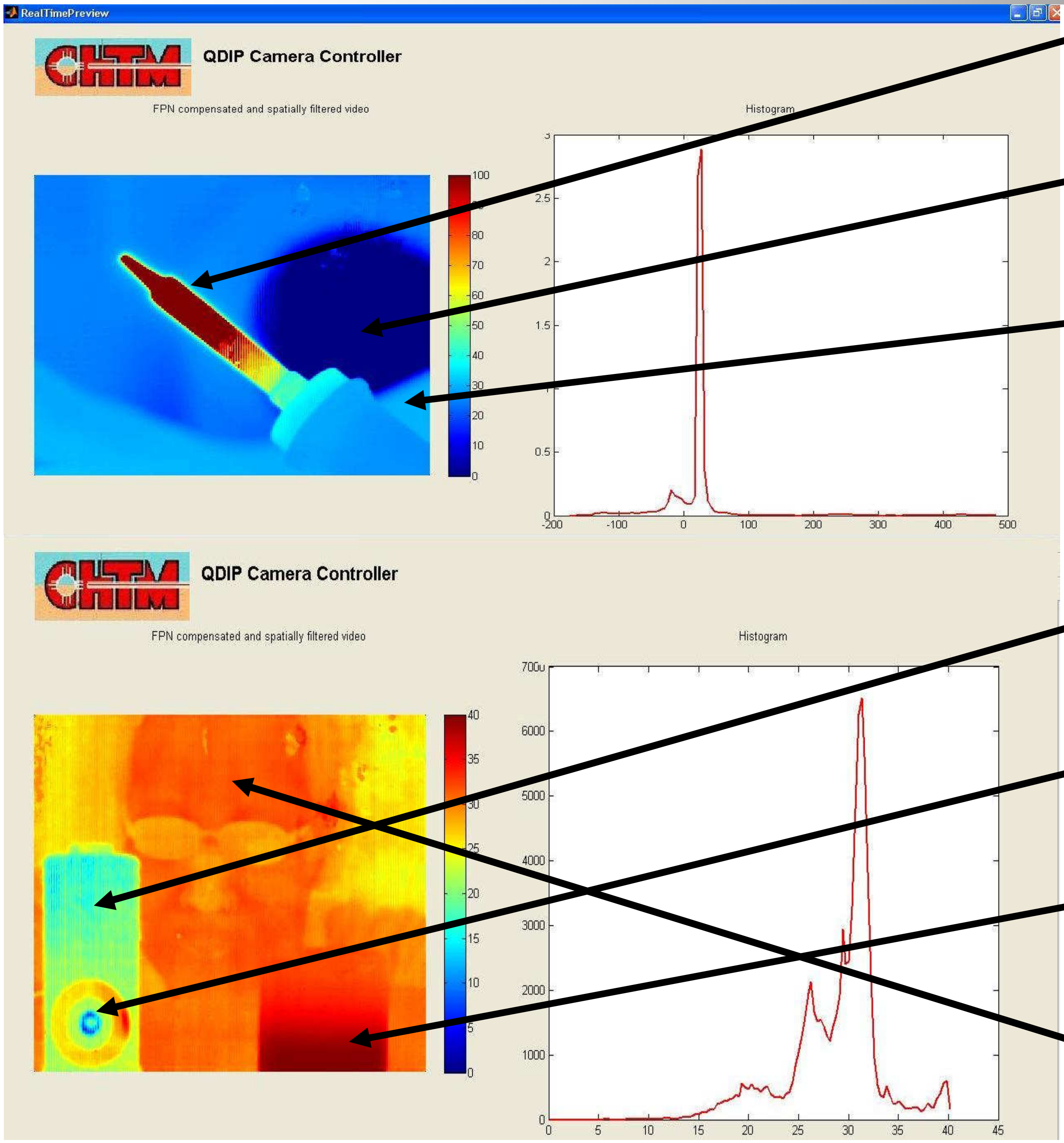
■ Multiple-point NUC scenes of DDWELL FPA

■ Multiple-point NUC in real time was tested with five different temperatures (26 ~ 30 °C).

■ FPA temperature = 60 K, Frame rate = 30 Hz, Int. time = 11.52 ms and Bias = 1.0 V.
3 ~ 12 μm lens was used.

■ Bad pixel replacement and spatial filtering were used to optimize the scene.

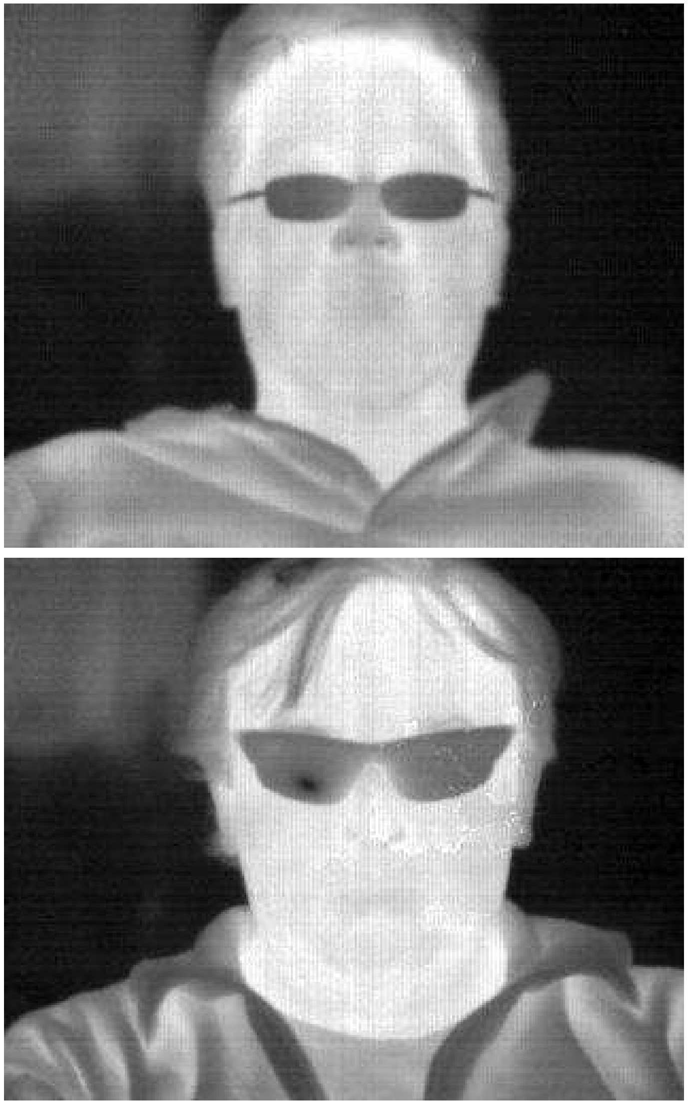
Demonstrations of Temperature Measurement



- Soldering iron: > 70 °C (~ red)
- Cold source: < 10 °C (~ dark blue)
- Arm: ~ mid 30 °C (~ light blue)
- False-color display

- Cooled InSb detector surface: between 15 and 20 °C (~ light blue)
- near detector aperture: ~ 5 °C or less (~ dark blue)
- Cup with hot water: > 35 °C (~ dark blue)
- Face: ~ mid 30 °C (~ light red)

Visual Comparisons between Commercial Two-point NUC and Multiple-point NUC



■ Facial images of DDWELL FPA corrected with commercial two-point NUC.

■ Corrected images by multiple-point NUC (9 points from 26 to 60 °C).

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5. Development and Performance of Non-Uniformity Correction (NUC)
6. **<u>Conclusions</u>**

■ The second generation DWELL FPA was developed by optimizing the device growth and processing learned from the first generation device structure. **Higher operating temperature was observed on the second generation device**.

■ DWELL FPAs were characterized for various device operating temperatures and biases. Performances were evaluated by NEDT and compared to QWIP FPA**. Performance results demonstrate our DWELL device is "improving" toward QWIP.**

■ Bias-tunability and multi-color capability of DWELL FPAs were demonstrated with various optical filters**.**

■ Bias-tunability was further examined for NH_3 and SF_6 gas detections**.**

■ Real-time multiple-point NUC was successfully developed and implemented to DWELL FPA as a post-processing algorithm.

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